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VARIABLE STARS IN THE DDO 187 DWARF GALAXY[1,2]

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ABSTRACT

Twelve pulsating variable stars have been discovered in the dwarf irregular galaxy DDO 187. Two of these are Cepheids based on CCD photometry on 29 nights spread over 13 years. Three more stars are possible Cepheids. The remaining 7 stars are all long-period variables (LPVs). The definite Cepheids lead to a new distance modulus for this galaxy of $m - M = 29.24 \pm 0.33$, corresponding to 7.0 ± 1.2 Mpc. We discuss the nature of the LPVs and show that a self-consistent interpretation of these can be made that supports the Cepheid distance.

Key words: Cepheids — galaxies: dwarf — galaxies: stellar content — Miras

1. INTRODUCTION

DDO 187 is a gas-rich dwarf irregular galaxy (also known as UGC 9128) located at $\alpha = 14^{h}15^{m}56^{s}$, $\delta = +23°03'$ (J2000.). Fisher & Tully (1979) show a green photograph of this galaxy that is partially resolved into stars. They note that star formation is not occurring uniformly across the disk but is concentrated toward one end of the galaxy. DDO 187 has long been considered to be a kinematic twin of the dwarf irregular GR 8 (DDO 155), which is thought to be a member or near neighbor of the Local Group (Yahil, Tammann, & Sandage 1977; Tolstoy et al. 1995). Hoessel (1986) produced a color-magnitude diagram (CMD) for the brightest resolved stars and from this estimated a distance modulus of $m - M = 28.8$ for DDO 187. Aparicio et al. (1988) produced a CMD from independent observations and estimated $m - M = 28.2 \pm 0.6$. Thus the photometric distances place DDO 187 considerably beyond the Local Group. Distance estimates in the range 3–4 Mpc have been used to estimate general characteristics of this interesting galaxy.

Skillman, Kennicutt, & Hodge (1989) found a very low value for the oxygen abundance of $12 + \log \mathrm{O/H} = 7.36$, corresponding to about 3% of solar. Lo, Sargent, & Young (1993) list a heliocentric H I velocity for DDO 187 of 153 km s^{-1} and an H I mass of $5 \times 10^{7}\ M_{\odot}$. The galaxy exhibits a chaotic velocity field with most of the velocity width of 36 km s^{-1} due to random motions; a rotation speed of 5 km s^{-1} is indicated by their results. Patterson & Thuan (1996) have done surface photometry in the B and I passbands for DDO 187. Their maps clearly confirm that the blue stars are concentrated on one-half of the disk. They derive an exponential scale length of 0.25 kpc from the brightness profile of this very small galaxy assuming a distance of 4 Mpc. Strobel, Hodge, & Kennicutt (1991) identified six small H II regions, which lie primarily over the bright blue half of this galaxy.

Given the interesting morphology of DDO 187 and its resolution into brighter stars, we began a program in 1981 to monitor its variable star population in the hope of finding Cepheid variables to establish a firm distance. The brightest stars indicated a distance in the range 4–6 Mpc, making this a challenging target for medium-sized ground-based telescopes. In this paper we show that the distance is even larger than these earlier estimates.

2. OBSERVATIONS

Imaging observations of DDO 187 were obtained on 29 separate nights beginning in 1981 and ending in 1994. They were made in the Thuan & Gunn (1976, hereafter TG) photometric system with the repeated period coverage frames obtained using the r filter. A variety of telescope, instrument, and CCD detector combinations were used over the period. A journal of these observations is presented in Table 1. Telescopes used were the 5 m reflector at Palomar Observatory (labeled as P5 in Table 1) and the 2.1 m telescope at the Kitt Peak National Observatory (labeled as K2.1 in Table 1). The different instrument/detector combinations are identified in Table 1 as follows: the PFUEI, described by Gunn & Westphal (1981); the PMP, described by Hoessel & Danielson (1983); the 4-Shooter, described by Gunn et al. (1987); and the T1KA and TI2 CCD detectors attached to the 2.1 m Gold Guider plus filter assembly. T1KA and TI2 are Kitt Peak National Observatory designations, which are 1024 and 800 square devices, respectively. Not all images were obtained under perfectly photometric conditions, but two epochs were photometric with system standard star observations available. The process for standardizing all the images, including those obtained through thin clouds and therefore only good for relative photometry, is described in § 3 below. Observations were obtained with FWHM seeing conditions in the range 0".8–1".4, with most of the images near 1".0. Pixel scales

[1] Observations obtained at the Kitt Peak National Observatory, National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

[2] Observations obtained at the Palomar Observatory, California Institute of Technology.

TABLE 1

OBSERVATION JOURNAL

U.T. Date	HJD	Telescope	Instrument
1981 May 6.......	2,444,730.87663	K2.1	PFUEI
1982 Mar 1.......	2,445,029.99659	K2.1	PMP
1983 May 18......	2,445,472.77620	P5	PFUEI
1983 Jul 5.........	2,445,520.77511	P5	PFUEI
1983 Jul 6.........	2,445,521.76323	P5	PFUEI
1983 Jul 7.........	2,445,522.75759	P5	PFUEI
1983 Jul 8.........	2,445,523.73043	P5	PFUEI
1984 Mar 7.......	2,445,766.91567	P5	4SHOOTER
1984 Mar 10......	2,445,769.89567	P5	4SHOOTER
1984 Mar 11......	2,445,770.90961	P5	4SHOOTER
1984 May 24......	2,445,844.87447	P5	4SHOOTER
1985 Mar 23......	2,446,147.94684	P5	4SHOOTER
1991 Jan 13.......	2,448,270.03337	K2.1	T1KA
1991 Feb 13......	2,448,301.03513	K2.1	TI2
1991 Mar 12......	2,448,327.95337	K2.1	TI2
1991 Apr 13......	2,448,359.93812	K2.1	TI2
1991 Apr 14......	2,448,360.79437	K2.1	TI2
1991 May 13......	2,448,389.87224	K2.1	TI2
1992 Jan 13.......	2,448,635.02085	K2.1	T1KA
1993 Mar 18......	2,449,064.98904	K2.1	T1KA
1993 Mar 22......	2,449,068.99681	K2.1	T1KA
1993 Mar 23......	2,449,069.99059	K2.1	T1KA
1993 Mar 24......	2,449,070.98715	K2.1	T1KA
1993 Mar 30......	2,449,076.97132	K2.1	T1KA
1994 Mar 5.......	2,449,416.93291	K2.1	T1KA
1994 Mar 6.......	2,449,418.00657	K2.1	T1KA
1994 Mar 10......	2,449,421.98176	K2.1	T1KA
1994 Mar 11......	2,449,422.96236	K2.1	T1KA
1994 Mar 16......	2,449,427.99452	K2.1	T1KA

varied between 0″.3 and 0″.5; the procedure for handling this variation as well as the different detector orientations on the sky will be described in § 3.

In Figure 1 we show a color photograph made from g, r, and i CCD frames taken on 1983 July 8. This picture clearly shows the segregation of the blue and red populations in this galaxy. The i frame viewed individually shows that the luminous red stars are uniformly distributed over the galaxy, while the color image shows the blue stars concentrated in what appears to be a relatively large association in the southwest half of the galaxy. As shown in Figure 2 below, no variable stars are found within this blue association. We believe that this is a selection effect due to the relatively high background and crowding in this region. Photometry carried out in this area is likely to be of blended objects rather than of individual stars.

3. DATA PROCESSING

The data processing techniques used here are identical to those described by Saha & Hoessel (1990, hereafter SH90) and refined by Hoessel et al. (1994, H94). Relative photometry of each individual epoch was done independently. Each image was transposed and/or reflected so the general orientations were the same. Individual pixel values were strictly preserved in this process. Point-spread function (PSF) photometry was done using the DAOPHOT package (Stetson 1987). This produced relative magnitudes for each object detected on each frame. For nonvariable stars these values differ from one another by a single constant zero-point offset plus random photon noise and measurement errors. The deepest frame with the best seeing of 0″.8 FWHM was obtained on 1984 May 24. The central portion of this frame is shown in Figure 2. Some 2600 individual objects were detected and magnitudes produced for this image. This frame was chosen as the master template frame for position registration and object matching.

No photometric zero point was available for this night. Observations in g, r, and i of TG standard stars along with DDO 187 were obtained on 1983 July 8 and 1991 April 13. On each night aperture extractions were performed for five brighter stars ($18.5 < r < 21.5$) on the DDO 187 field as well as for seven TG system standard stars. Transformations of the standard star observations to the TG system yielded residuals less than 0.01 mag on both nights. The rms scatter among the resulting aperture magnitudes for the five DDO 187 reference stars between the two epochs was 0.06 mag. The 1983 data set was judged superior for this purpose because of the higher signal-to-noise ratio in the Palomar 5 m data. Transformations from it were used to set the final magnitude zero points. These final aperture magnitudes were then compared with the results from the PSF fits for the same five stars, and an offset determined, which was then applied to all the data on this night. The rms scatter in PSF − aperture residuals was 0.06 mag. This value is somewhat worse than normal in our experience and is probably the result of the variability of the PSF over the field of view in the PFUEI instrument.

The spatial mapping between the master template frame of 1984 May 24 and the photometric frame of 1983 July 8 was evaluated using the positions of 10 stars and an analytic linear transformation function that included translation, scale, and rotation. This yielded a mapping between the frames accurate to better than 0″.6 over the field. Given this transformation the individual stars were matched using their DAOPHOT output coordinates to the same object on the master frame. Then a magnitude offset was derived using 100 brighter stars, and this offset was applied to standardize the master frame. Determination of the photometric zero points between the frames can be done to better than 0.01 mag using this approach. Finally, all of the remaining 27 DAOPHOT output files were transformed to the master coordinate system and zero point using this same methodology. The final output of this process is a file containing positions, magnitudes, and errors for each star on each epoch it was detected—all on the same coordinate and photometric system.

4. DETECTION OF VARIABLES AND PERIOD DETERMINATION

The methods used in the detection of variables and their period determination are those defined in SH90 and H94. They start from the basis that the error estimates for each star detected at a number of different epochs are assumed to be Gaussian, therefore following a χ^2 distribution from which a probability of variability can be calculated for each star. Thus a list of stars with at least 12 observations and a formal probability of less than 0.5% of being nonvariable was generated. This process produces a large number of candidates due to non-Gaussian noise sources such as cosmic rays, contamination from nearby objects, charge trails from saturated objects, charge traps, and bad columns. The next step was to further refine this list by requiring the objects to be periodic. The periodicity test was based on the Lafler & Kinman (1965) algorithm, which provides a "goodness of periodicity" statistic. Objects with very large brightness variation are also retained regardless of whether they are periodic. However, there were no such candidates found in this galaxy. A total of 63 candidate

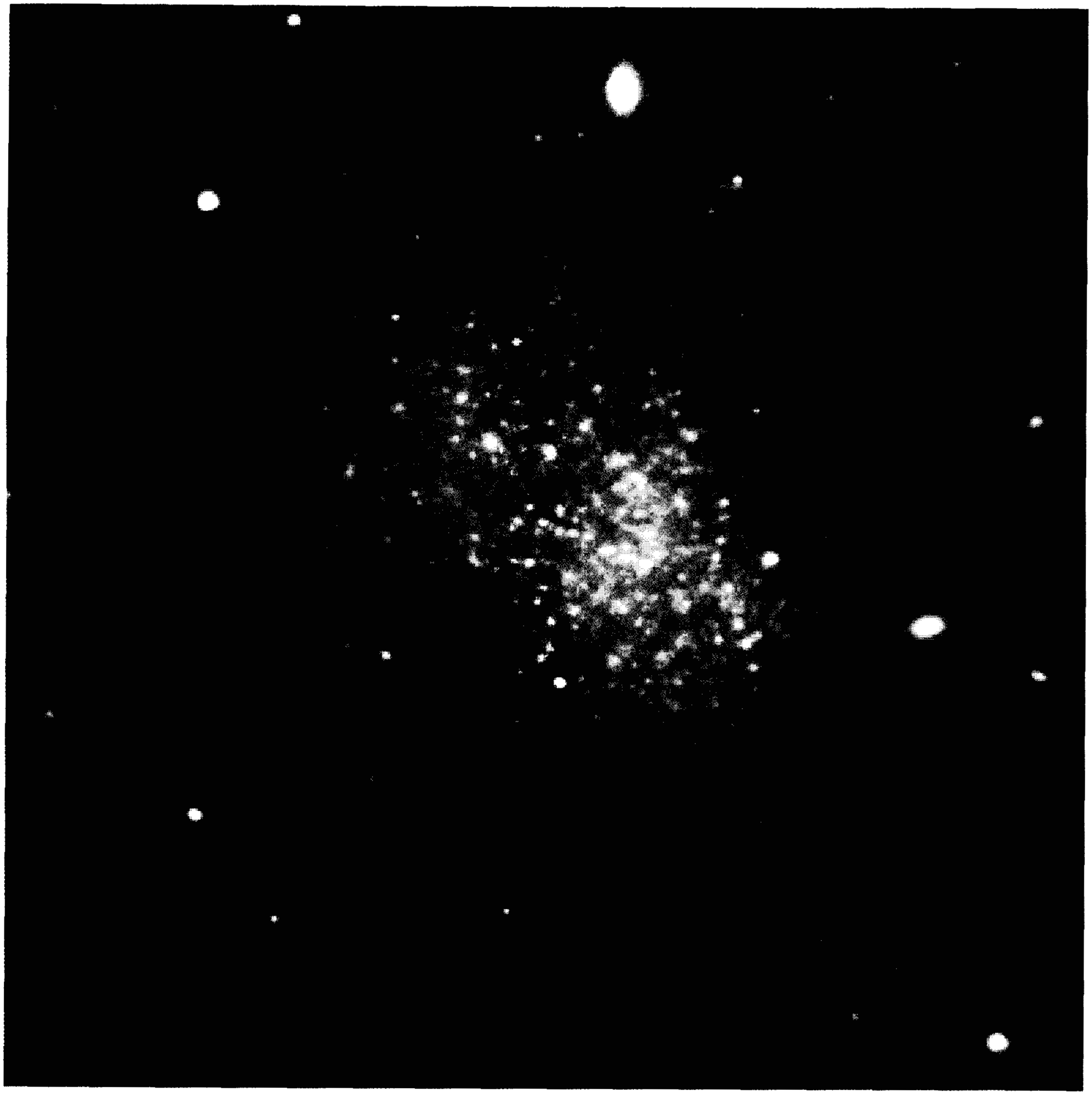

FIG. 1.—Color image of DDO 187 made using the PFUEI instrument at the Palomar Hale telescope on 1983 July 8. The region shown is 2.'8 on each side. North is up and east at the left. Separate frames with g, r, and i filters were combined to make this image. Note the segregation of the younger, bluer resolved stars in the southwest half of the galaxy.

variables was produced by the automated process. DDO 187 is a relatively distant target, given the resolution and signal-to-noise ratio of our data set; thus we expected that careful manual examination of each candidate would be necessary, particularly because of the crowding in the blue association. The next step was to manually blink several epochs for each putative periodic variable to identify those that were still caused by some defect in the data. Then for the remaining candidates, the most likely period range was explored interactively and the most likely period chosen, again using the Lafler & Kinman algorithm. At this step only those stars with very high quality pulsator-type light curves that showed a low chance of being aliased in period were kept. The resulting 12 pulsating variables are identified in Figure 2. The photometry for each epoch for each star is given in Table 2. Uncertainties quoted in this table are those produced by the PSF-fitting program; for final uncertainties these numbers must be combined with another 0.08 mag because of the zero point and photometric transformations. In Figure 3, we present the final light curves for these objects, and in Table 3, we list the periods, the phase-weighted mean magnitudes (as defined in H94), and $g-r$ and $r-i$ colors where the signal-to-noise ratio was adequate for these final stars. Uncertainties in the periods range from 1% for the shorter period stars to 10% for the periods near 900 days. The short-period objects are more prone to

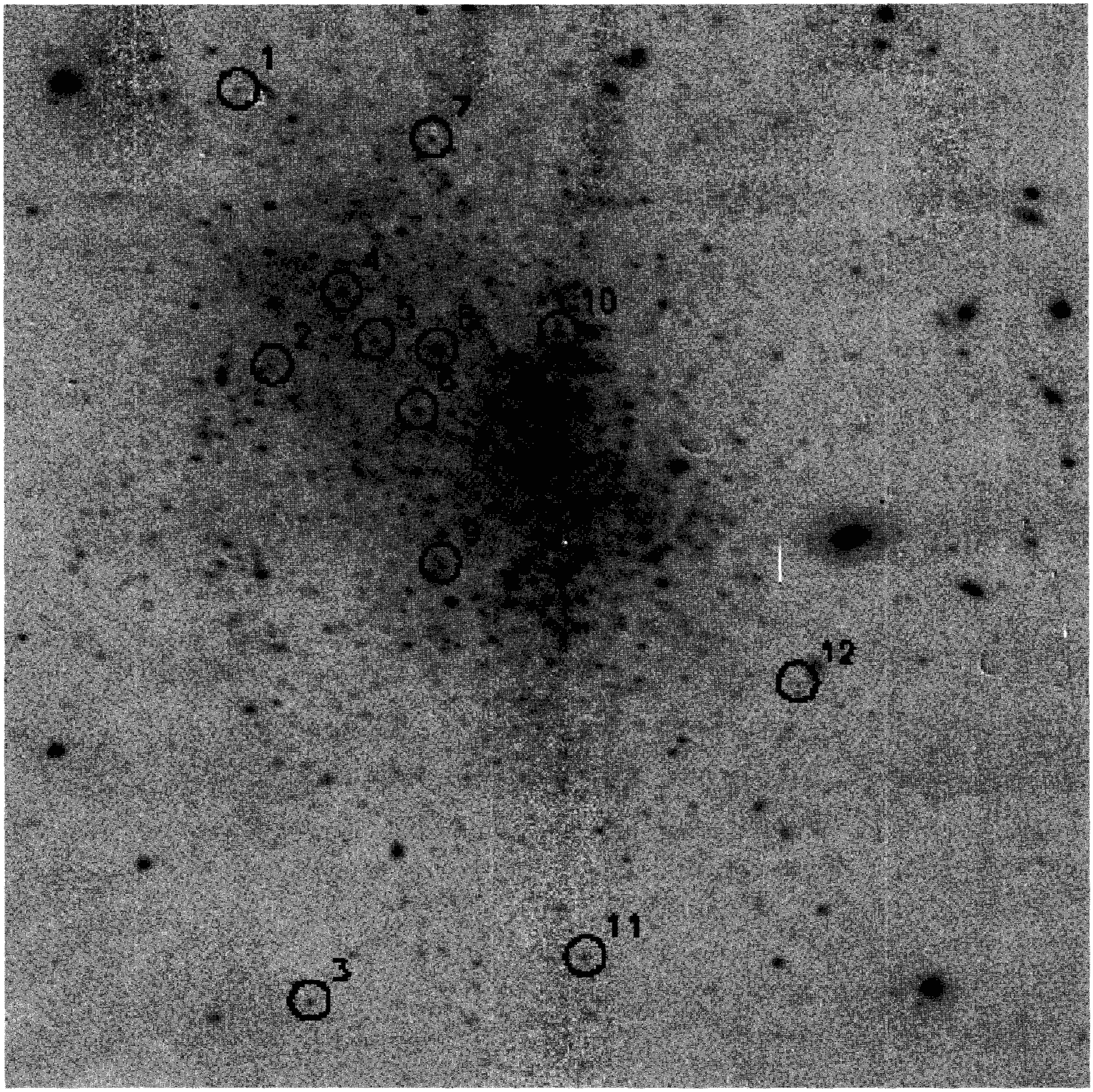

FIG. 2.—Image of DDO 187 obtained on 1984 May 24 using chip 2 of the 4SHOOTER with a Thuan & Gunn r filter at the Palomar Hale Telescope. The picture is centered near $\alpha = 14^h15^m56^s$, $\delta = +23°03'$ (J2000.0), and is 2'.8 on each side. North is up and east to the left. The 12 final pulsating variables are labeled on the frame.

aliasing, where several aliases cluster about the true period. Thus for the short periods, the overall uncertainty is more realistically about 5%. The colors are uncertain for the fainter stars, with an error near 0.3 mag at $r = 23.5$ mag. Note also that the colors in Table 3 are not mean colors (we do not have phase coverage in passbands other than r), but instantaneous colors from observations in two passbands on the same night. Thus they are additionally uncertain to the degree that they can vary over the pulsation cycle. Thus they should not be used for anything other than indicative purposes, at the 0.1 to 0.3 mag level. No short-period (<20 days) stars were found in DDO 187, although our time sampling is adequate to find such stars. The time-series data for each star in this list was extensively investigated over the period range from 5–1000 days with more attention paid to the longer periods than we have in the past.

5. PERIOD-LUMINOSITY DIAGRAM AND DISTANCE

The period-luminosity (P-L) diagram for the 12 variables is plotted in Figure 4. Given their variability, it is extremely unlikely that any of these are foreground objects; we believe that they are all likely members of DDO 187. The stars appear to divide into two clear categories, a group of five stars with periods less than 100 days, which we believe are likely Cepheid variables (*circles*), and a second group of

TABLE 2

Photometry of Variable Stars: Magnitudes and Error Estimates

HJD	V1	V2	V3	V4	V5	V6
2,444,730.8766......	23.57 ± 0.20	22.80 ± 0.11	23.44 ± 0.16	21.32 ± 0.03	21.67 ± 0.04	23.19 ± 0.16
2,445,029.9966......	...	23.43 ± 0.22	23.72 ± 0.13	21.88 ± 0.08	22.99 ± 0.18	22.67 ± 0.18
2,445,472.7762......	23.18 ± 0.16	23.05 ± 0.16	23.38 ± 0.20	21.45 ± 0.04	21.05 ± 0.03	22.88 ± 0.15
2,445,520.7751......	...	22.85 ± 0.15	23.46 ± 0.26	21.26 ± 0.04	20.72 ± 0.02	22.78 ± 0.20
2,445,521.7632......	23.08 ± 0.13	...	23.73 ± 0.18	21.40 ± 0.03	20.80 ± 0.02	22.90 ± 0.11
2,445,522.7576......	23.21 ± 0.14	22.82 ± 0.12	23.51 ± 0.18	21.31 ± 0.03	20.83 ± 0.02	23.02 ± 0.13
2,445,523.7304......	23.30 ± 0.11	23.16 ± 0.11	23.85 ± 0.16	21.30 ± 0.06	20.85 ± 0.02	22.63 ± 0.14
2,445,766.9157......	23.46 ± 0.14	23.17 ± 0.14	23.23 ± 0.09	...	22.30 ± 0.08	22.52 ± 0.18
2,445,769.8957......	23.16 ± 0.11	23.08 ± 0.11	23.16 ± 0.08	21.32 ± 0.06	22.38 ± 0.05	22.47 ± 0.08
2,445,770.9096......	23.30 ± 0.11	23.42 ± 0.14	23.33 ± 0.12	21.42 ± 0.03	22.43 ± 0.05	22.73 ± 0.07
2,445,844.8745......	23.38 ± 0.12	23.55 ± 0.12	23.00 ± 0.08	21.42 ± 0.08	22.56 ± 0.06	22.33 ± 0.16
2,446,147.9468......	23.41 ± 0.13	22.93 ± 0.10	23.16 ± 0.10	21.63 ± 0.04	22.80 ± 0.08	23.00 ± 0.12
2,449,068.9968......	...	23.52 ± 0.12	23.43 ± 0.09	21.59 ± 0.02	21.63 ± 0.02	23.83 ± 0.15
2,449,069.9906......	23.06 ± 0.09	23.26 ± 0.08	23.41 ± 0.10	21.67 ± 0.04	21.72 ± 0.02	24.27 ± 0.29
2,449,064.9890......	...	23.34 ± 0.31	23.22 ± 0.24	21.51 ± 0.06	21.70 ± 0.07	...
2,449,070.9871......	...	...	23.55 ± 0.17	...	21.69 ± 0.03	23.72 ± 0.22
2,449,076.9713......	23.30 ± 0.13	23.33 ± 0.13	23.94 ± 0.18	21.67 ± 0.03	21.73 ± 0.02	24.21 ± 0.31
2,449,416.9329......	23.73 ± 0.13	...	23.48 ± 0.09	21.61 ± 0.02	23.07 ± 0.08	23.22 ± 0.09
2,449,418.0066......	23.93 ± 0.28	...	23.43 ± 0.13	21.68 ± 0.04	23.18 ± 0.10	23.40 ± 0.25
2,449,421.9818......	23.47 ± 0.10	22.59 ± 0.09	23.49 ± 0.12	21.71 ± 0.02	23.00 ± 0.05	22.97 ± 0.06
2,449,422.9624......	23.72 ± 0.23	...	23.31 ± 0.12	21.68 ± 0.03	23.17 ± 0.11	23.36 ± 0.14
2,449,427.9945......	23.53 ± 0.12	22.97 ± 0.09	23.57 ± 0.09	21.65 ± 0.02	23.11 ± 0.08	23.03 ± 0.12
2,448,270.0334......	23.06 ± 0.09	22.70 ± 0.07	23.02 ± 0.07	21.38 ± 0.02	21.59 ± 0.02	23.41 ± 0.11
2,448,635.0208......	23.44 ± 0.16	23.14 ± 0.12	23.66 ± 0.16	21.49 ± 0.03	...	...
2,448,301.0351......	...	...	23.07 ± 0.15	...	21.88 ± 0.06	24.17 ± 0.50
2,448,327.9534......	23.05 ± 0.14	...	...	...	22.51 ± 0.08	24.15 ± 0.33
2,448,359.9381......	...	...	...	22.02 ± 0.04	22.50 ± 0.05	23.18 ± 0.09
2,448,360.7944......	23.19 ± 0.11	23.14 ± 0.08	...	22.09 ± 0.03	22.55 ± 0.05	23.31 ± 0.11
2,448,389.8722......	23.10 ± 0.13	...	23.33 ± 0.13	22.05 ± 0.04	23.01 ± 0.08	23.48 ± 0.16

HJD	V7	V8	V9	V10	V11	V12
2,444,730.8766......	...	20.82 ± 0.04	22.48 ± 0.13	...	23.53 ± 0.17	...
2,445,029.9966......	23.69 ± 0.20	21.31 ± 0.06	...	...	23.46 ± 0.13	23.21 ± 0.18
2,445,472.7762......	22.95 ± 0.11	22.14 ± 0.06	...	22.85 ± 0.12	24.47 ± 0.51	...
2,445,520.7751......	22.85 ± 0.15	21.63 ± 0.05	21.99 ± 0.09	23.50 ± 0.26	...	...
2,445,521.7632......	23.15 ± 0.13	21.80 ± 0.06	22.17 ± 0.16	23.07 ± 0.14	23.38 ± 0.16	24.06 ± 0.34
2,445,522.7576......	...	21.66 ± 0.06	21.86 ± 0.10	22.64 ± 0.11	23.57 ± 0.23	...
2,445,523.7304......	22.85 ± 0.08	21.61 ± 0.04	22.16 ± 0.14	23.11 ± 0.09	23.55 ± 0.12	24.07 ± 0.21
2,445,766.9157......	23.39 ± 0.14	...	22.18 ± 0.06	23.13 ± 0.13	23.58 ± 0.16	24.02 ± 0.29
2,445,769.8957......	23.19 ± 0.10	19.69 ± 0.12	22.28 ± 0.13	23.25 ± 0.08	23.77 ± 0.16	22.43 ± 0.08
2,445,770.9096......	...	...	22.38 ± 0.16	23.13 ± 0.09	23.84 ± 0.12	...
2,445,844.8745......	22.89 ± 0.11	...	22.31 ± 0.13	23.20 ± 0.08	23.64 ± 0.13	23.86 ± 0.17
2,446,147.9468......	...	21.92 ± 0.04	22.49 ± 0.08	23.23 ± 0.08	...	22.80 ± 0.08
2,449,068.9968......	23.35 ± 0.09	21.95 ± 0.03	22.61 ± 0.06	23.63 ± 0.16	23.27 ± 0.08	23.21 ± 0.08
2,449,069.9906......	...	21.95 ± 0.03	...	23.25 ± 0.08	...	23.39 ± 0.07
2,449,064.9890......	23.89 ± 0.48	...	...	...	22.83 ± 0.15	23.09 ± 0.21
2,449,070.9871......	23.40 ± 0.13	21.95 ± 0.04	...	23.35 ± 0.16	23.32 ± 0.14	23.57 ± 0.22
2,449,076.9713......	23.33 ± 0.11	21.96 ± 0.03	...	23.38 ± 0.13	23.24 ± 0.10	...
2,449,416.9329......	...	22.16 ± 0.07	22.74 ± 0.11	23.71 ± 0.21	23.38 ± 0.10	23.11 ± 0.08
2,449,418.0066......	23.71 ± 0.15	22.19 ± 0.07	...	...	23.16 ± 0.09	22.95 ± 0.12
2,449,421.9818......	23.67 ± 0.11	22.10 ± 0.03	22.94 ± 0.13	23.35 ± 0.09	23.35 ± 0.07	22.97 ± 0.06
2,449,422.9624......	...	22.05 ± 0.04	22.71 ± 0.16	23.96 ± 0.26	23.22 ± 0.26	22.93 ± 0.10
2,449,427.9945......	...	22.05 ± 0.05	22.80 ± 0.14	23.15 ± 0.07	23.27 ± 0.06	22.86 ± 0.04
2,448,270.0334......	23.02 ± 0.06	21.80 ± 0.03	22.74 ± 0.16	23.42 ± 0.12	23.25 ± 0.09	23.01 ± 0.07
2,448,635.0208......	23.27 ± 0.14	19.82 ± 0.01	22.21 ± 0.08	...	23.36 ± 0.11	...
2,448,301.0351......	...	21.95 ± 0.07	22.36 ± 0.09	...	22.97 ± 0.14	...
2,448,327.9534......	...	22.21 ± 0.05	...	...	...	...
2,448,359.9381......	23.21 ± 0.11	21.96 ± 0.03	22.25 ± 0.04	...	...	23.28 ± 0.10
2,448,360.7944......	23.25 ± 0.13	22.01 ± 0.06	22.20 ± 0.05	23.94 ± 0.20	23.02 ± 0.08	23.55 ± 0.11
2,448,389.8722......	23.51 ± 0.10	22.02 ± 0.03	22.48 ± 0.05	23.60 ± 0.14	23.33 ± 0.09	...

seven stars with periods longer than 300 days. This second group appears to further subdivide into a group of four stars with average magnitudes near $r = 23$ mag and periods of several hundred days (*diamonds*), and a group of brighter stars with periods near 1000 days (*squares*). Alves & Cook (1995) show light curves for objects with similar periods in M101 at similar average apparent magnitudes and amplitudes. They concluded that in their case these were predominantly variables among the red supergiants. They did not, however, see a distinct subdivision into the groups mentioned above. The nature of these objects is investigated in § 5.2 of this paper. In Figure 5, we show g, r, and i CMDs for all the resolved stars in DDO 187. The variables listed in Table 3 are shown, with symbols as defined in Figure 4.

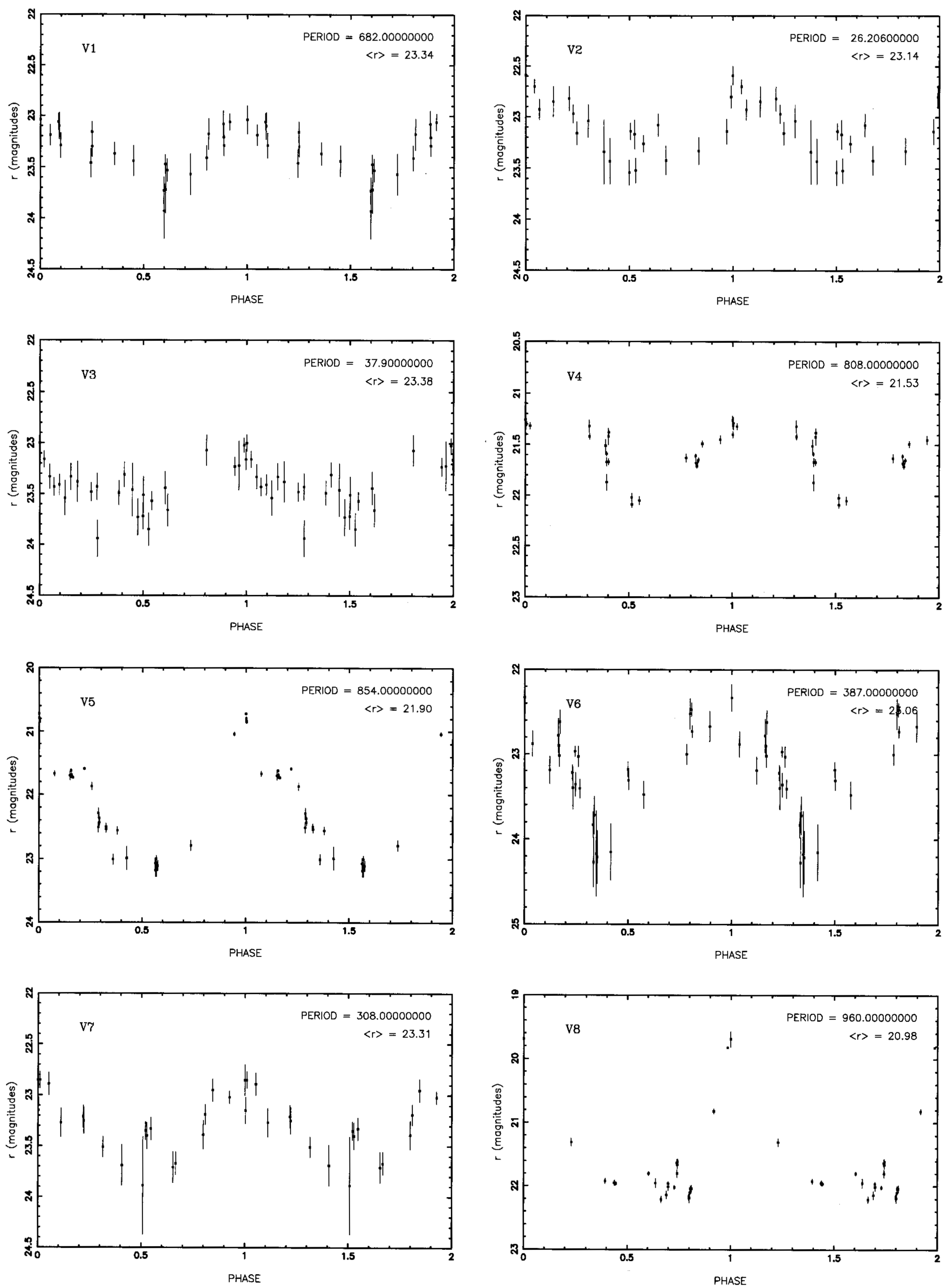

FIG. 3.—Light curves for 12 pulsating variables in DDO 187. These stars are identified in Fig. 2. Periods and phase-weighted average *r* magnitudes are indicated for each star.

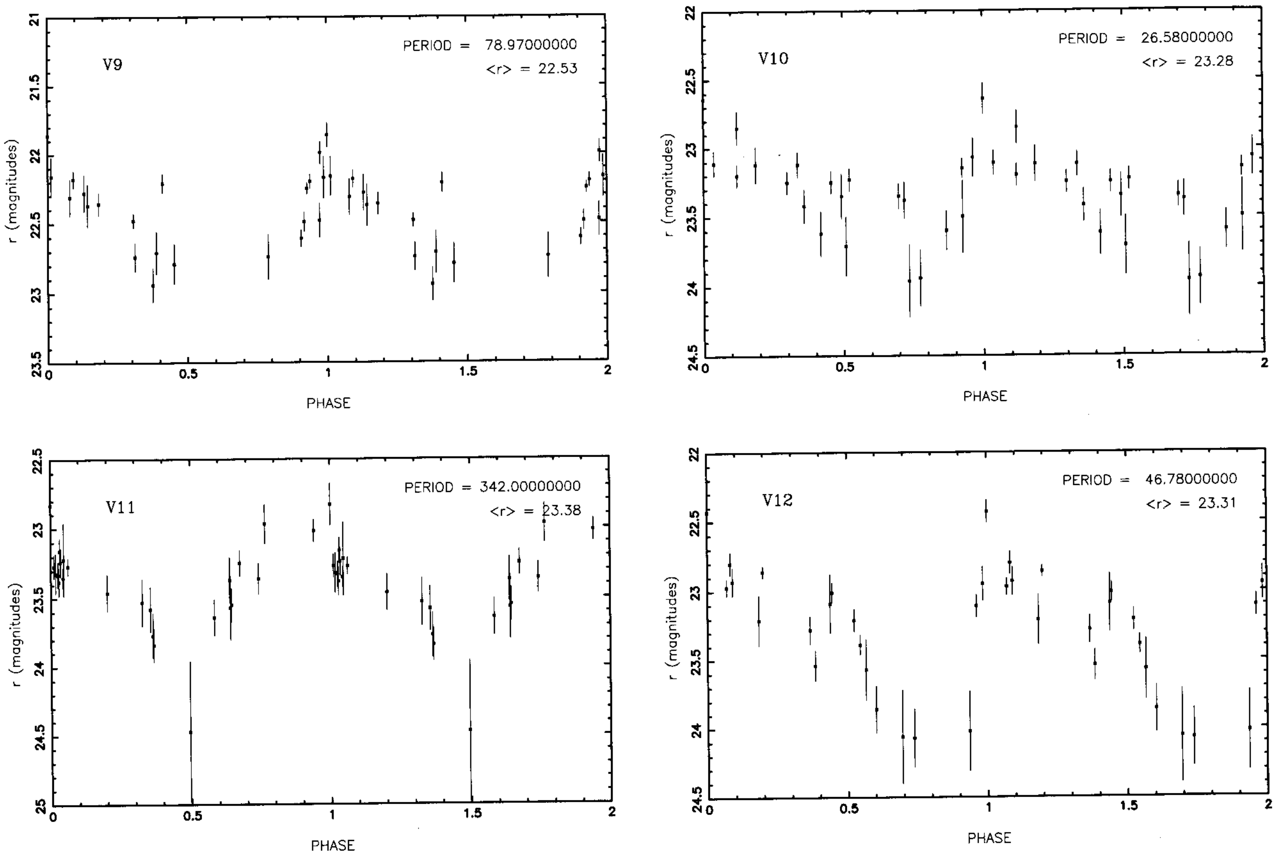

FIG. 3.—*Continued*

5.1. *Cepheid Candidates*

Group 1 contains V2, V3, V9, V10, and V12. Light curves and colors of V9 and V12 indicate that they are very likely long-period Cepheid variables (Fig. 4, *filled circles*). V2 and V10 are possible Cepheids with lower quality light curves. As is seen in Figures 1 and 2, they are in quite crowded regions, and it is likely that their magnitudes are systematically measured as too bright. These objects could especially benefit from higher resolution observations, either with the *Hubble Space Telescope* or an adaptive optics system. V3 is located far out in the galaxy, its light curve is of only fair quality and its color is uncertain because this image is blended with other objects, but the best estimate is perhaps too red for a Cepheid. It may be a star from Group 2 with an aliased period, but we were not able to fit any long period to this object. We will thus group it as a possible Cepheid in the remaining analysis. The solid line in Figure 4 is a fit of the Cepheid P-L relation of Madore & Freedman (1991) as transformed to the TG system by H94 to the two best Cepheid candidates V9 and V12. The relation $M_r = -2.91(\log P - 1) - 4.04$ is best fit with an apparent distance modulus of $m - M = 29.24$. Fitting this relation to all five Cepheid candidates (V2, V3, V9, V10, and V12) produces a modulus of $m - M = 28.91$. This result is illustrated by the dashed line in Figure 4. We believe that the first value is more reliable given the higher quality of the data for these

TABLE 3

VARIABLE STAR CHARACTERISTICS

ID	$\langle r \rangle$	Period	$g - r$	$r - i$
V1	23.34	682.0	0.98	0.77
V2	23.14	26.21	0.13	−0.22
V3	23.38	37.90	0.65	1.94
V4	21.53	808.0	0.98	0.27
V5	21.90	854.0	0.97	1.22
V6	23.06	387.0	...	0.48
V7	23.31	308.0	1.00	0.49
V8	20.98	960.0	0.70	1.27
V9	22.53	78.97	0.04	0.19
V10	23.28	26.58	...	0.17
V11	23.38	342.0	0.74	0.74
V12	23.31	46.78	0.42	0.84

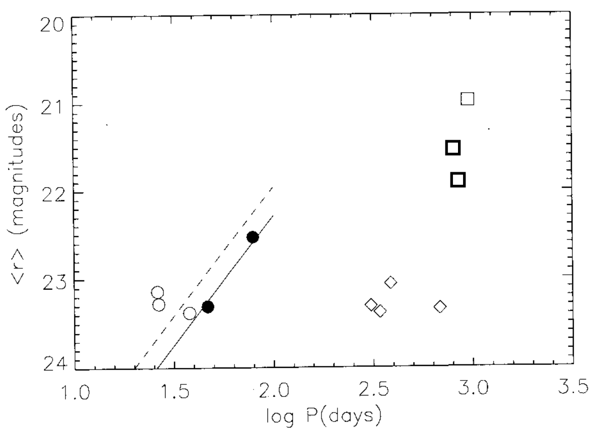

FIG. 4.—Period-luminosity diagram for the 12 variables. Represented are Cepheids (*filled circles*), probable Cepheids (*open circles*), red supergiant variables (*diamonds*), and the unusual objects discussed in the text (*squares*). The solid line represents the Cepheid P-L relation from Madore & Freedman (1991) after transformation to the Thuan & Gunn photometric system and application of an apparent distance modulus of $m - M = 29.24$. The dashed line is the same relation using a distance modulus of 28.91, which is the fit including the three less secure Cepheid candidates.

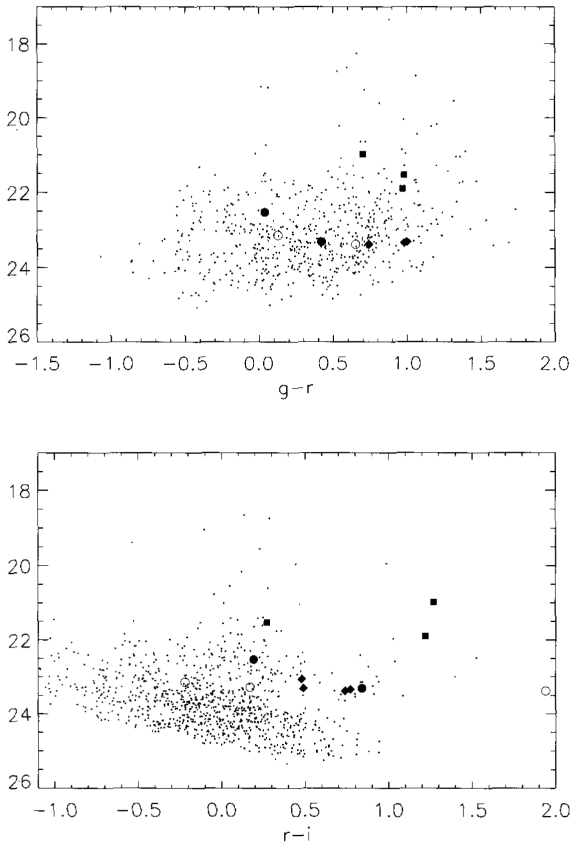

FIG. 5.—CMDs for DDO187. The resolved stars observed are plotted as a (r, $g-r$) CMD in the upper panel and as a (r, $r-i$) CMD in the lower panel. The variable stars listed in Table 3 are shown with the same symbols as defined for Figure 4. These points represent the instantaneous magnitudes and colors of the variables at a single epoch. The errors in magnitude are 0.3 at $r = 23.5$.

two stars. The difference between these two results of 0.33 mag is close to a 1 σ error—we will adopt it as the uncertainty in the apparent Cepheid distance.

The foreground extinction in the direction toward DDO 187 can be estimated from the H I column density maps of Heiles (1975), following the method of Burstein & Heiles (1978), as applied to the TG system by Schneider, Gunn, & Hoessel (1983). This results in an upper limit for the extinction of $A_r = 0.02$ mag, which we will ignore. This estimate ignores any internal extinction within DDO 187 and possible calibration errors in the P-L relation (which are thought to be of order 5%). Our conclusion, with these and the other caveats discussed above, is that DDO 187 is at a distance of 7.0 ± 1 Mpc.

5.2. *Long-Period Variables*

Interpretation of the nature of the very long period variables in DDO 187 is difficult and no a priori definitive classification of the seven longer period stars (V1, V4, V5, V6, V7, V8, and V11) is possible. One possibility is that some or all of these objects are asymptotic giant branch (AGB) stars; another is that they are evolved massive supergiant variables. Wood et al. (1983, WBF) have extensively studied long-period variables in the Magellanic Clouds. They distinguish between these two types of LPVs (i.e., AGB stars versus red supergiants). AGB stars have degenerate cores with hydrogen- (and helium-) burning shell(s). Their luminosity is governed by their core mass, and the Chandrasekhar limit on the core mass therefore limits the maximum luminosity of such objects to $M_{\rm bol} \approx -7.1$ mag (WBF). In the Thuan-Gunn r passband this corresponds to $M_r = -5.20$ (Kinman, Mould, & Wood 1987, hereafter KMW). These stars have a P-L relation in $M_{\rm bol}$ that is well projected in the K passband but shows large scatter in the visible passbands. The data at hand are insufficient to predict bolometric or K-band magnitudes. Unfortunately, as demonstrated by KMW, an attempt at a P-L relation in the r band results in a scatter diagram. Assuming our Cepheid distance modulus of $m - M = 29.24$, the expected maximum brightness of such AGB stars in DDO 187 is near $r = 24.0$ mag, which is fainter than the limit of our observations. However, the light curve properties of the variables shown as diamonds in Figure 4 are consistent with them being AGB stars. The brightest of these stars has $\langle r \rangle = 23.06$. Thus the maximum brightness of this class of objects of $M_r = -5.20$ implies a maximum apparent distance modulus to DDO 187 of only 28.26. Thus, either these stars are not AGB stars or we have misclassified the Cepheids.

Could these objects instead be red supergiant variables? From their supergiant LPVs in M33, KMW show that the K-band and bolometric P-L relations follow the same respective slopes as for the LMC, with a brightness offset consistent with their distance ratio. Alves & Cook (1995) show that the four supergiant LPVs found by them in M101 show similar properties for bolometric magnitudes. The KMW data also show a P-L relation for supergiant LPVs in the r band (presumably since the colors of supergiant LPVs are better behaved than for AGB variables, WBF). The apparent mean magnitude $\langle r \rangle$ changes from 18.3 at period of 539 days to 18.9 at a period of 815 days, with scatter of 0.1 mag for the five stars involved, which corresponds to M_r ranging from -6.3 to -5.7 mag over the same period interval. Using the periods and $\langle r \rangle$ values for the five supergiant LPVs found by KMW and the four objects in DDO 187 we can perform a slide fit for a P-L relation against the red supergiant variables in M33. This yields a best difference in apparent r modulus of 4.82 mag and an rms scatter of 0.06 mag in the fit. For a M33 modulus of 24.60, this yields a modulus for DDO 187 of 29.4 ± 0.5 mag, which is consistent with the derived Cepheid distance. In addition, the amplitudes of 0.5–1.0 mag for these stars are consistent with those expected for supergiant red variables. We would need better color information to identify whether these have colors consistent with supergiant LPVs (Wood et al. 1983 show that such stars are very tightly constrained in $\langle J-K \rangle$). Such a confirmation would bolster our distance estimate from the Cepheid variables.

Three stars have yet to be considered: V4, V5, and V8, which are the most luminous and longest period stars. Variables of this sort have been found in most dwarf irregular galaxies (Sandage et al. 1996) and are frequently identified as red stars near the Eddington and/or Humphreys-Davidsen limit (e.g., Humphreys 1983) on CMDs for the galaxies (for example see the CMD for DDO 187 by Aparicio et al. 1988). Note that in such figures the average magnitudes for the variables are usually quite uncertain because of the large amplitudes of the stars and observations with little or no phase coverage. We know of no case for dwarf irregular galaxies other than DDO 187 in which strictly periodic behavior has been established. Many studies have found that the average absolute magnitudes of the three most luminous red stars in resolved galaxies cluster near $M_V = -7.9$ (e.g., Sandage et al. 1996 and references therein) at least for galaxies with $M_B < -14.0$. We can only speculate that perhaps some of these objects in other dwarf irregular galaxies are in fact periodic but have not been observed long enough to establish periodicity. V8 has the highest luminosity of the variables in DDO 187, with an average apparent magnitude of $r = 20.98$. This value transforms to $V = 21.39$. Assuming V8 is equivalent to the average of the objects used in other galaxies, a distance estimate of $m - M = 29.29$ would be the result—this is quite consistent with the value derived from the Cepheids. Recently, Heger et al. (1997) have investigated the pulsational properties of red supergiants (RSG) with very high luminosity-to-mass ratio. They find that such RSG stars can exhibit variations in the amplitude, luminosity, and period ranges of interest.

Let us examine the consequences of interpreting these three brightest stars as members of the well-studied classes of observed red variables. If they are variables of the sort studied by KMW, then we can apply their P-L relation to these stars. V4 has a poorly determined light curve, and we have probably missed important phase points, so this star will not be used in further analysis. Applying the KMW P-L relation to V5 and V8 yields distance moduli of 27.6 and 26.7, respectively. The large amplitudes for these stars of 2.4 and 2.5 mag, respectively, argue against their being supergiant variables as studied by KMW since the latter have amplitudes of only a few tenths of a magnitude. AGB variables can have such large amplitudes. If V8 was identified as a maximum luminosity AGB star a distance modulus of 26.2 would be implied. It is not possible with the available data to completely rule out these alternatives to the Cepheid-based apparent distance modulus of $m - M = 29.24$, but this value is our best estimate. The self-consistent explanation is that the stars marked as diamonds in Figure 4 are red supergiant variables found in other Local Group galaxies and that the brightest three stars are the ultraluminous RSG variables of the sort modeled by Heger et al. (1997).

6. DISCUSSION

A consistent case for a distance of 7 Mpc can be made for DDO 187 from Cepheid variables, red supergiant variables, and the brightest red variable star. This new estimate for the distance of DDO 187 is larger than previous values and is clearly at the limit of the available data. It would be very desirable to obtain deeper images in order to find the more numerous expected shorter period Cepheids. Confirmation of this result will be difficult without higher resolution observations, which would be best obtained with the *HST*. We note that no variables were found in the younger, bluer region of the galaxy, where one might expect at least some of the Cepheids to reside. We believe this is due to the high crowding in this region and the variable seeing conditions in the data set. We were not able to adequately fit shorter periods than those listed above for any of the variables even though in our procedure it is usually easiest to find short periods. This leads us to conclude that a much smaller distance for DDO 187 is unlikely.

DDO 187 is projected on the sky far from any of the nearby groups of galaxies (as is well illustrated in Tully & Fisher 1987). The two closest concentrations of galaxies in angle on the sky at low-recession velocity are the CVn I cloud and the M101 group. IC 4182 is thought to be a CVn I member; its Cepheid distance is 4.7 Mpc (Sandage et al. 1992; Saha et al. 1994). M101 has a Cepheid distance of 7.4 Mpc (Kelson et al. 1996). Thus DDO 187 is actually quite distant from both groups. Our distance of 7 Mpc for DDO 187 suggests that it is either an outlying member of the M101 group or that it is a field dwarf irregular galaxy.

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